Estimating the probable maximum flood in UK catchments using the ReFH model

Date revised: 15/06/2020

Authors:

Samuel Pucknell BEng[1]

Thomas Rodding Kjeldsen MSc, PhD[1]

Tracey Haxton BSc, MSc, C.WEM, MCIWEM[2]

Jude Jeans C.WEM, MCIWEM, PIEMA[2]

Andrew R. Young BSc (Jt. Hons), MSc, PhD[2]

[1]Department of Architecture and Civil Engineering, University of Bath, BA2 7AY

[2]Wallingford HydroSolutions, Wallingford, OX10 8BB

Corresponding author: Thomas Kjeldsen

Email: trk23@bath.ac.uk

Document statistics:

Number of words: 2702

Number of figures: 2

Number of tables: 4

Abstract

This paper presents a first attempt at formulating a complete framework for estimating the probable maximum flood (PMF) in UK catchments using the Revitalised Flood Hydrograph (ReFH) model. The framework translates most of the guidelines developed for the FSR/FEH rainfall-runoff model, but a new method for estimating initial soil moisture in line with the ReFH loss model is proposed. The framework has been tested using both ReFH 2.2 and ReFH 2.3 against previously published PMF results for 15 reservoired catchments and found to provide comparable and credible results.

Key words

Dams, barrages & reservoirs. Floods & floodworks. Hydrology & water resource.

List of symbols

Symbol	Meaning	Units
C_{ini}	Initial soil moisture depth	mm
C_{max}	Maximum soil moisture depth	mm
CWI	Catchment wetness index	mm
DPR_{CWI}	Dynamic percentage runoff dependent on CWI	%
DPR_{RAIN}	Dynamic percentage runoff dependent on P	%
P	Total design storm depth	mm
PMP	Total depth of a design PMP storm	mm
PR	Percentage runoff	%
SPR	Standard percentage runoff	%
ΔPR	Absolute difference in percentage runoff	%

Introduction

Estimation of the probable maximum flood (PMF) is an important part of reservoir safety considerations in the United Kingdom for category A dams, where a breach could endanger lives in a downstream community (ICE, 2015). The current guidelines for estimating PMF, as detailed in the fourth edition of the Floods and Reservoir Safety publication (ICE, 2015) stipulate that estimates of PMF should be derived as outlined in Volume 4 of the Flood Estimation Handbook (Institute of Hydrology, 1999) using the FSR/FEH rainfall-runoff model combined with estimates of the probable maximum flood (PMP) published as part of the Flood Studies Report (NERC, 1975).

The FSR/FEH rainfall-runoff model is an event-based model converting a rainfall event (observed or design event) into a corresponding flood hydrograph. The model was first published as part of the Flood Studies Report (NERC, 1975) and later revised as part of the Flood Estimation Handbook (IH,

1999) to be compatible with electronic catchment descriptors and a revised design rainfall model. While the model is still recommended for use in reservoir safety, it has effectively been replaced by the Revitalised FSR/FEH rainfall-runoff model (ReFH) for use in most fluvial design flood estimation studies. The first release of the ReFH model was limited to estimating events with a return period up to 150 years (Kjeldsen 2007). An updated version of the model was proposed by Kjeldsen et al. (2013) mainly considering the effects of urban development, and Wallingford HydroSolutions (2017) released an updated version of the model, ReFH2, compatible with the FEH13 Depth-Duration-Frequency rainfall model (Stewart et al., 2013) enabling simulation of design events up to a return period of 1000 years. While design events with return periods between 100-1000 years are routinely used in management of fluvial flood risk, they are still far below the requirements of 10,000 year events and PMF events required for reservoir safety considerations. Simulation of design events up to a return period of 10,000 years was enabled within the ReFH2.3 software, released in November 2019. Pether and Fraser (2019) highlighted the complexity of the current guidelines for design flood estimation for reservoir safety in the UK, involving different methods for different return period. MacDonald and Scott (2000) critiqued the use of the FSR/FEH model for use in design flood estimation for reservoir safety, and Faulkner and Benn (2016) suggested that a move from the FSR/FEH methodology to ReFH might be warranted, but noted that ReFH was designed for smaller events and that further research into the applicability for modelling PMF events is required. In the light of this discussion, the aim of the current study is to investigate how best to combine the ReFH model with PMP rainfall events to generate credible estimates of PMF, and to investigate the sensitivity of the resulting PMF estimates to change in key input parameters.

The FSR/FEH model

The FSR/FEH model is described in detail by Houghton-Carr (1999) and consists of three components: a loss model, a routing model and a baseflow model. The purpose of the loss model is to calculate the fraction of the total rainfall volume that is transformed into direct runoff; percentage runoff (PR). To simulate a design flood event for a given return period, the loss model calculates PR as a combination of a static and two dynamic terms as

$$
\begin{gathered}
PR = SPR + DPR_{CWI} + DPR_{RAIN} \\
DPR_{CWI} = 0.25(CWI - 125) \\
DPR_{RAIN} = \begin{cases} 0 & P \leq 40mm \\ 0.45(P-40)^{0.7} & P > 40 \end{cases}
\end{gathered}
\tag{1}
$$

where SPR is the static standard percentage runoff (%) often obtained from the SPRHOST catchment descriptor, DPR_{CWI} is the dynamic effect from antecedent soil moisture as measured by the catchment wetness index (CWI), and DPR_{RAIN} is the dynamic effect from the rainfall magnitude, depending on the total rainfall volume P.

When simulating a PMF event, the probable maximum precipitation (PMP) event is combined with a revised version value of CWI used based on the estimated maximum antecedent rainfall as described by Houghton-Carr (1999).

The ReFH model

The initial ReFH model was developed by Kjeldsen et al. (2005). The model consists of a loss-model, a routing model and a baseflow model, mirroring the structure of the FSR/FEH rainfall-runoff model. Development of the ReFH model was motivated by shortcomings of the FSR/FEH model and benefitted from updates in hydrological modelling methodology and a more comprehensive database of observed flood events for model calibration. A comprehensive description of the ReFH model and subsequent updates is provided by Kjeldsen (2007) and Wallingford HydroSolutions (2019).

The most substantial change between ReFH and the original FSR/FEH model is the introduction of a new loss model concept, which has implications for PMF estimation. The purpose of the loss model is to estimate the percentage of the total rainfall that is transformed into direct runoff, i.e. percentage runoff. The ReFH loss model has one parameter, C_{max} which provides a conceptual realisation of the maximum soil moisture depth and one boundary condition, the initial soil moisture depth, C_{ini}. While C_{max} stays constant, C_{ini} is a dynamic boundary condition that can vary between events. The percentage runoff is calculated as a function of C_{max}, rainfall depth P (mm) and C_{ini} as

$$PR = \frac{C_{ini}}{C_{max}} + \frac{P}{2C_{max}} \quad (2)$$

The first term on the right-hand side is a measure of the initial soil moisture while the second represent the dynamic rainfall effects. Thus, the ReFH model represent the same fundamental dynamics as the FSR/FEH loss model, relating PR to antecedent soil moisture and rainfall volume. The model parameter C_{max} can be estimated either from analysis of observed flood events or via a regression model linking model parameters to catchment descriptors. Unlike the FSR/FEH model, the losses in the ReFH model are calculated for each time step of the simulation to account for the wetting-up of the soil moisture during the flood event.

Estimating the Probable maximum flood

The FSR/FEH procedures for estimating PMF requires key input variables to be adjusted to represent "*ultra conservative assumptions*" (NERC, 1975) reflecting the seriousness of reservoir safety considerations. Estimation of PMF events using the ReFH model therefore needs to translate these considerations into equivalent adjustments of ReFH input variables. The following five input variables are explicitly considered: probable maximum precipitation event, frozen ground, snow melt, antecedent soil moisture, and reduction in catchment response time. A summary of how the input factors are considered in the FSR/FEH model and the proposed changes in ReFH are listed in Table 1.

Table 1: Guidelines for PMF estimation for the FSR/FEH model and proposed guidelines for the ReFH model.

Input variable	FSR/FEH	ReFH
Probable maximum precipitation event	Use FSR methodology	Use FSR methodology
Snow melt	42 mm/day	42 mm/day
Reduction in catchment response time	Reduce Time-to-peak by 33%	Reduce Time-to-peak by 33%
Frozen ground	A minimum SPR value of 53%	A minimum PR value of 53%
Antecedent soil moisture	Increase CWI	Increase C_{ini}

It is proposed that no changes are made to the actual PMP design rainfall event and that the snow-melt ratio of 42 mm/day are both maintained. Similarly, the 33% reduction in Time-to-peak (Tp) is maintained for the ReFH model. Note that a minimum value of Tp of 1hr is recommended in the ReFH model for the rural compartment of a catchment, and lower values should be used with caution. For the urban compartment of a catchment *Tp* is scaled by a factor that is less than unity to represent the enhanced routing of runoff within urban areas. Thus, *Tp* in the urban compartment can be less than 1 (Wallingford HydroSolutions, 2019).

Translation of elevated antecedent soil moisture and frozen ground adjustments from the FSR/FEH model to ReFH are less straight-forward, as the ReFH model is based on a conceptual hydrological model rather than a direct representation of percentage runoff. The FSR suggested accounting for frozen ground conditions by assuming all soils across the catchment could be categorised WRAP class 5, i.e. the most impermeable class of soils in the FSR methodology. For the FSR/FEH method this was translated into a minimum value of SPR of 53%. While this mostly will result in actual PR values in excess of 53%, a minimum PR value of 53% was imposed on the ReFH model. Further research into representation of frozen soils in the ReFH model is clearly needed.

In both the FSR/FEH and the ReFH models, percentage runoff is determined by the antecedent soil moisture and total rainfall. In this study the necessary upward adjustment of the initial soil moisture of the ReFH model was estimated by first considering the absolute difference (increase) ΔPR between the percentage runoff as derived for a T-year event and for the PMF when using the FSR/FEH method (eq. 1) combined with the PMP event. This difference represents the effect of the frozen ground adjustment and increased catchment wetness (CWI) when simulating the PMF event.

Next, the absolute difference in percentage runoff ΔPR is added directly to the percentage runoff derived from the ReFH model (Eq. 2). Finally, the corresponding value of C_{ini} (denoted C_{ini}^{PMF}) is calculated by re-arranging the ReFH loss model as

$$C_{ini}^{PMF} = (PR_{ReFH} + \Delta PR)C_{max} - \frac{1}{2}PMP \qquad (3)$$

where PMP is the total depth of the PMP event. The procedure outlined above will occasionally result in adjusted values of C_{ini}^{PMF} that cause estimates of percentage runoff in excess of 100%. This is clearly untenable and in such cases the percentage runoff was capped at 100%.

Case study

The Institute of Hydrology Report 114 (IH 114) by Reed and Field (1992) provided estimates of PMF for 15 reservoired catchment, evenly distributed across upland areas of the UK. A summary of the catchments is provided in Table 2, including key catchment descriptors such as catchment area, standard annual average rainfall (1960-1990), and BFIHOST extracted from the FEH Service (CEH, 2018). Note that the IH114 study was conducted before the availability of digital FEH catchment descriptors, and therefore the catchment areas originally published in IH114 differs slightly from the areas reported in Table 1 but are within 8% (apart from one catchment) which is considered a reasonable deviation. For each catchment Reed and Field (1992) estimated PMF both including and excluding reservoir effects. In this study the comparison is based on the PMF excluding reservoir effects.

Table 2: Details of 15 reservoired catchments from Reed and Field (1992)

Catchment	**Area (km^2)**	**SAAR (mm)**	**BFIHOST**	**Region**
Loch Craisg	0.74	1156	0.3660	Scotland
Little Denny	0.98	1247	0.5110	Scotland
Loch Gleann	1.21	1763	0.3760	Scotland
Parkhill House	1.21	780	0.7210	Scotland
Leperstone	1.22	1517	0.6090	Scotland
Higher Naden	3.9	1479	0.4080	England
Lower Carriston	3.94	808	0.5890	Scotland
Nanpantan	4.28	717	0.3510	England
Upper Neuadd	5.74	2243	0.3220	Wales
Crafnant	6.2	2142	0.4190	Wales
Usk	13.5	1694	0.3700	Wales
Colt Crag	18.05	784	0.2910	England
Loch Kirbister	20.73	1068	0.4690	Scotland
Staunton Harold	26.3	671	0.5070	England
Roadford	34.69	1146	0.4160	England

For each of the 15 catchments, the ReFH model parameters were estimated based on the extracted catchment descriptors (Table 2) and the PMP design rainfall events developed according to the procedures outlined in the FEH Volume 4. Both the summer and winter PMP were calculated for each catchment. Snowmelt contribution was added to the winter PMP design rainfall events.

The four parameters for the ReFH2 model were estimated using the catchment descriptor equations. The estimated value of *Tp* was reduced by 33% in accordance with the PMF guidelines (Table 1), noticing a minimum value of 1hr.

Next, the initial soil moisture C_{ini}^{PMF} required by the ReFH model for simulating the PMF is estimated for each catchment using the procedure outlined above. For each catchment the difference ΔPR is calculated representing the difference between the values of PR when using the FSR/FEH loss model for PMF calculation and return period calculations. Figure 1 shows the ratio between the adjusted (C_{ini}^{PMF}) and the initial (default) values of C_{ini} (derived from catchment descriptors) for each of the 15 catchment for both summer and winter events plotted against C_{max} as estimated from catchment descriptors.

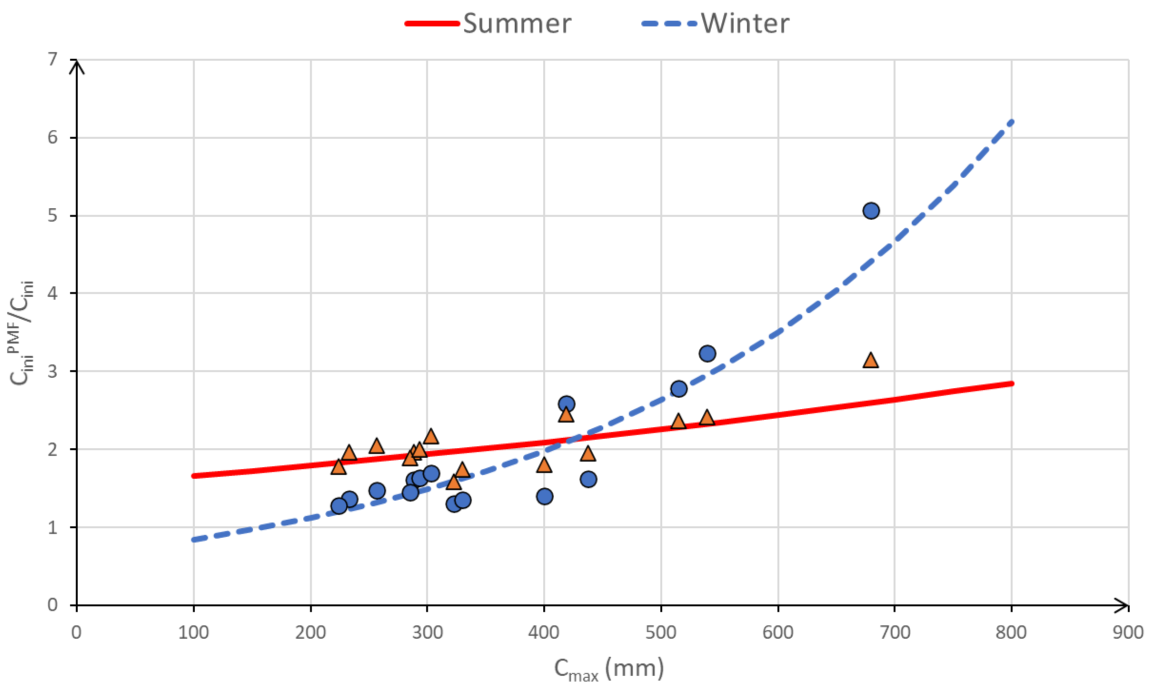

Figure 1: Observed and predicted values of C_{ini}^{PMF}/C_{ini} plotted as a function of C_{max} for 15 catchments (summer and winter).

To enable prediction of the ratio C_{ini}^{PMF}/C_{ini} for any given catchment, a general relationship between the ratio and C_{max} is proposed in the form of an exponential function for both the summer and winter observations as

$$C_{ini}^{PMF}/C_{ini} = a \times exp\left(b\frac{C_{max}}{1000}\right) \qquad (4)$$

The two parameters a and b are estimated using the method of least squares for both the summer and winter season. The outlier on the right-hand side of Figure 1, *Parkhill House,* has a higher value of C_{max} than the bulk of the catchments, representing the high value of BFIHOST. Separate sets of regression models were estimated with and without including this catchment, and the resulting parameters are summarised in Table 3.

Table 3: Model parameters for Eq. (4) estimated

	Summer		Winter	
	a	b	a	b
Incl. outlier	1.3695	1.1166	0.5522	3.2205
Excl. outlier	1.5368	0.7717	0.6339	2.8515

Using the set of model parameters derived without considering the data from the outlier yields a less step curve as C_{max} increases. This relationship is considered more cautious for use in extrapolations beyond the calibration range, and is therefore taken forward in the rest of this study.

Finally, the summer and winter PMF events are simulated using the ReFH model with PMP design rainfall events and the adjusted C_{ini} values. For each catchment the peak flow values of both the summer and winter PMF were extracted. A summary of the PMF peak flow events obtained from the adjusted ReFH model as well as the PMF estimates obtained for the same catchments by Reed and Field (1992) are shown in Table 4 and on Figure 2. The methodology has been developed and tested using the ReFH2.2 model and repeated using the ReFH2.3 model, which was released in November 2019. The PMF values derived using the ReFH2.3 model are also presented in Figure 2, which illustrates that the results are very similar to those derived using both ReFH2.2 and ReFH2.3.

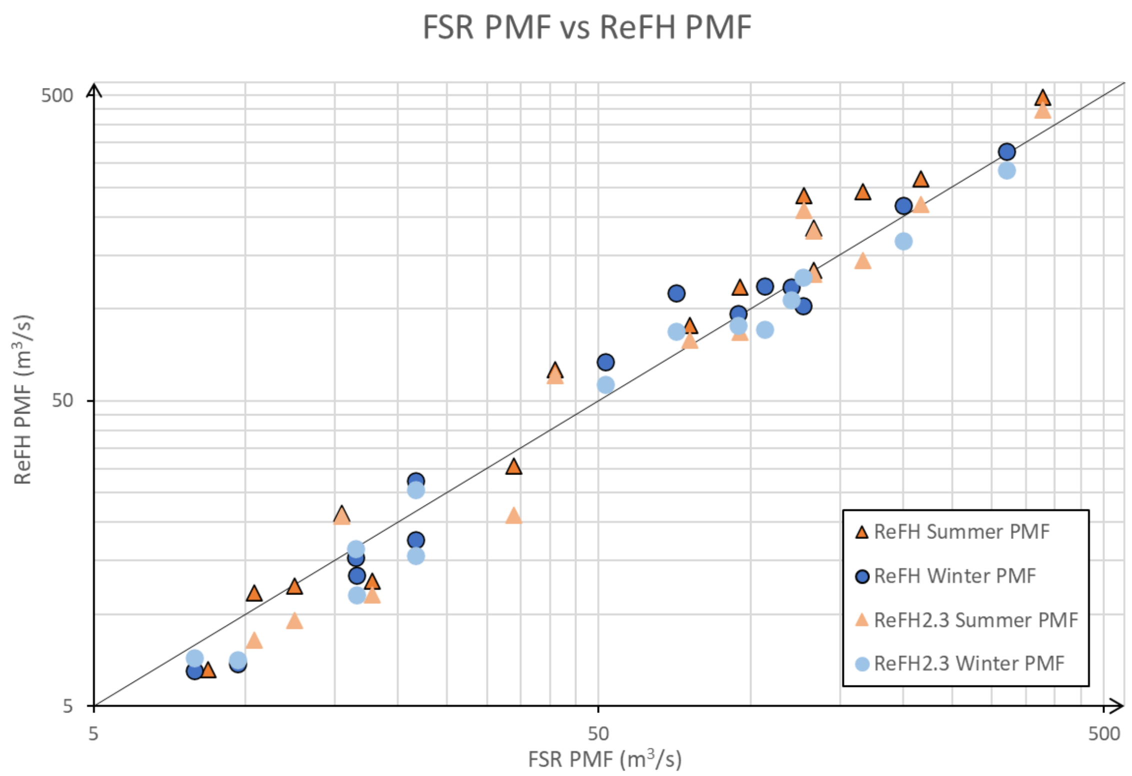

Figure 2: Comparison of PMF as estimated by the ReFH2 model (y-axis) and the FSR/FEH method (x-axis) for both summer (triangle) and winter (circle) events. ReFH2.3 results are presented for comparison.

Table 4: Estimates of summer and winter PMF obtained from the ReFH2.2 and the FSR/FEH models for all 15 test catchments

Catchment	ReFH2 PMF (m^3/s)	ReFH2 PMF Season	Summer event as % of PMF	Winter event as % of PMF	FSR PMF (m^3/s)	FSR PMF Season
Loch Craisg	11.8	S	100	56	10.4	S
Little Denny	12.4	S	100	56	12.5	S
Loch Gleann	21.4	S	100	72	15.51	W
Parkhill House	6.6	S	100	65	8.4	S
Leperstone	13.4	W	96	100	17.8	S
Higher Naden	88.2	S	100	76	75.6	S
Lower Carriston	30.7	S	100	57	33.9	S
Nanpantan	63.5	S	100	43	40.9	S
Upper Neuadd	133.4	S	100	88	133.3	S
Crafnant	117.9	S	100	82	95.1	S
Usk	267.2	S	100	82	217.4	S
Colt Crag	234.7	S	100	48	127.2	S
Loch Kirbister	184.8	S	100	55	133.2	S
Staunton Harold	242.4	S	100	49	166.4	S
Roadford	493.6	S	100	67	377.8	S

Figure 2 shows a direct comparison of final estimates of both summer and winter PMF from the FSR and ReFH model. In general, there is a good agreement between PMF estimates obtained by the two methods.

Discussion

The estimation of the probable maximum flood is a challenging problem as it requires numerous assumptions to be made concerning the flood producing mechanisms which cannot easily be validated against observed flood events. The procedures proposed in this paper should not be viewed as an authoritarian guide to estimation of PMF using the ReFH model. Rather, they constitute a first attempt at formulating and testing a new framework allowing the ReFH model to be used for PMF estimation, and that the resulting estimates are compatible with the existing methods. The results demonstrate that it is credible to finally move away from the FSR/FEH model for reservoir risk assessment towards adopting the ReFH model. Such a move would unify the design flood estimation methods in the UK within a common framework, and also allow the reservoir safety flood modelling to benefit from methodological developments made since the inception of the FSR model more than 50 years ago. The initial work was undertaken using ReFH 2.2 but initial tests using the more recent ReFH 2.3 model have confirmed the consistency of the method.

References

Faulkner, D. and Benn, J. (2016) Reservoir flood estimation: Time for a re-think. *In Dams–Benefits and Disbenefits; Assets or Liabilities?* Proceedings of the 19th Biennial Conference of the British Dam Society held at Lancaster University from 7–10 September 2016 (pp. 87-100). ICE Publishing.

Kjeldsen, T.R. (2007) The revitalised FSR/FEH rainfall-runoff method. *Flood Estimation Handbook Supplementary Report No. 1*, Centre for Ecology & Hydrology, Wallingford.

Kjeldsen, T.R., Miller, J.D. and Packman, J.C., 2013. Modelling design flood hydrographs in catchments with mixed urban and rural land cover. *Hydrology Research*, 44(6), pp.1040-1057.

Kjeldsen, T.R., Stewart, E.J., Packman, J.C., Folwell, S.S. and Bayliss, A.C. (2005) Revitalisation of the FSR/FEH rainfall-runoff method. *Final Report to DEFRA/EA project FD1913*.

Institution of Civil Engineers (2015) *Floods and Reservoir Safety*, 4th Edition, ICE Publishing, London, 71 pages.

Natural Environment Research Council (1975) *Flood Studies Report*, 5 Volumes, London.

Pether, R. and Fraser, R. (2019) A quick reference table for extreme flood hydrology methods in at UK dams. *Dams and Reservoirs*, 29(1), 41-42.

Reed, D.W. and Field, E.K. (1992) Reservoir flood estimation: another look. *Institute of Hydrology Report 114*, Institute of Hydrology, Wallingford.

Stewart E.J., Jones D.A., Svensson C., Morris D.G., Dempsey P., Dent, J.E., Collier C.G. and Anderson C.W. 2013. Reservoir Safety – Long return period rainfall. R&D Technical Report WS 194/2/39/TR (two volumes), *Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.*

Wallingford HydroSolutions. (2019) ReFH2 Technical Guide *https://refhdocs.hydrosolutions.co.uk*